Numerical Weather Prediction

Changes to the Nimrod Cloud Top Height Diagnosis

Forecasting Research Technical Report No. 424

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Reviewed by: Rod Brown (22/01/2003)

Authorised for Release: Rod Brown (24/01/2003)

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Abstract

This paper describes the new Nimrod algorithm for deriving cloud-top height from normalised Meteosat data and Mesoscale Model data. The algorithm, implemented in February 2003, searches for stable layers in the predicted Model temperature profile which can be fitted to the Meteosat IR cloud-top temperature. Atmospheric brightness corrections are applied to the Model temperature profiles. The algorithm aims to prevent cloud-top heights being erroneously placed where the Model has predicted a dry, conditionally unstable layer.

Case studies are detailed in this report, demonstrating how the algorithm works and situations, such as poorly defined inversions in the Model data, broken cloud and thin cirrus, where unsatisfactory results are returned.

The majority of cases which have been studied show that the CTH output will not cause problems in user programs.

Abstract 2
Introduction 2
Logic Changes 3
Stable Layer Algorithm (preferred) 4
Model Temperature Profile-matching Algorithm 5
Changes to Output 6
Case Studies 7
Successful Application of Stable Layer Algorithm 7
Successful Application of the Profile-matching Algorithm 9
Errors caused by Poorly Defined Model Inversions 10
Problems caused by Broken Cloud layers 11
Problems caused by Thin Cirrus clouds 12
Conclusion 13
Appendix: Logic Flow Chart 14
Formulaic Logic for Stable Layer Algorithm 15

Introduction

Cloud Top Height is derived from Meteosat fields and predicted Model fields. It is used in several Nimrod programs as a cloud diagnostic tool as well as part of the initialisation of the Mesoscale Model. Due to the errors in the input fields, it is difficult to produce an accurate Cloud Top Height (CTH) field. The object of this project was to produce realistic CTH values which would not cause problems such as instability in the Mesoscale Model, a problem which has been found to generate spurious convection and showers in the Model output.

This project follows a project completed in April 2002 where an attempt was made to detect and diagnose low level cloud (stratus or stratocumulus) below an inversion. A more general approach, using an algorithm which considers the whole of the troposphere and is not seasonally dependent, has been developed in this project.

This project looks only at the processing of First Generation Meteosat data which will be the primary source of satellite data in the Summer of 2003. It is planned to incorporate these concepts into the MSG cloud top height software.

Logic Changes

Major changes have taken place. The Normand's Point Algorithm, which sought to determine the CTH of shallow stratocumulus cloud from surface temperature and dew point values, and the Low Level Inversion logic, which sought to detect summer low level inversions above shallow cloud, have been replaced with a Stable Layer Algorithm.

The default model temperature profile matching algorithm has also been modified to use RTTOV predicted cloud top temperatures, but is still only used where the preferred stable layer algorithm has been unable to produce an acceptable result.

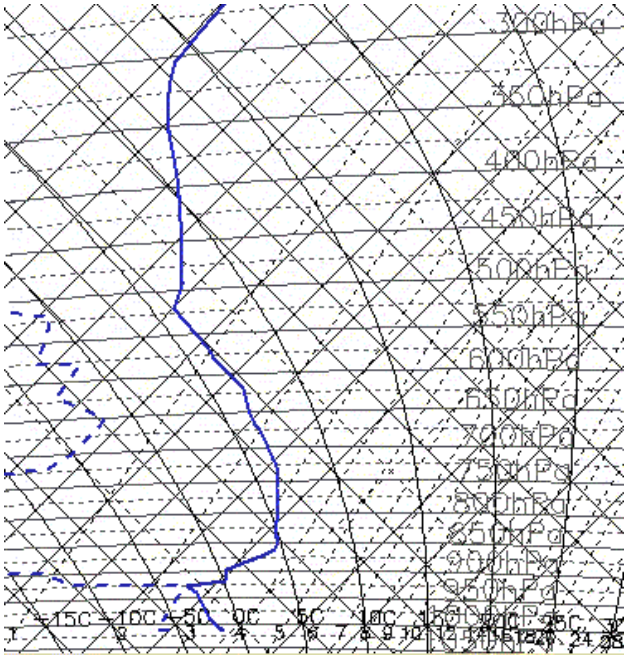


Figure 1 (above): Tephigram profile showing an Inversion-capped low level cloud

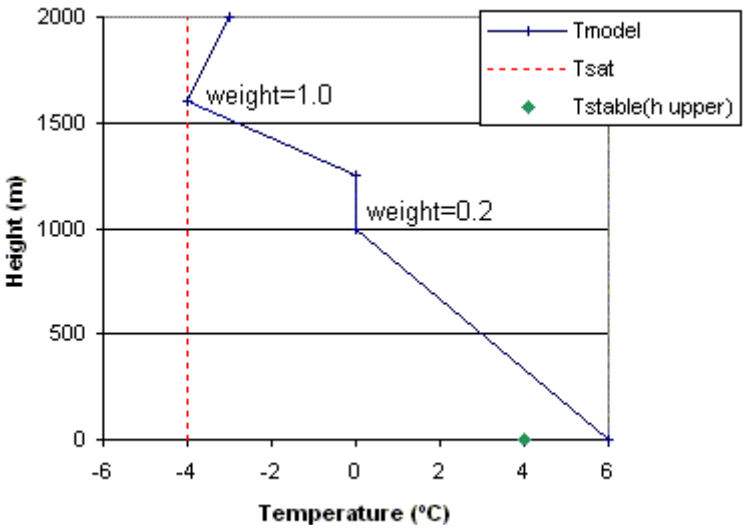
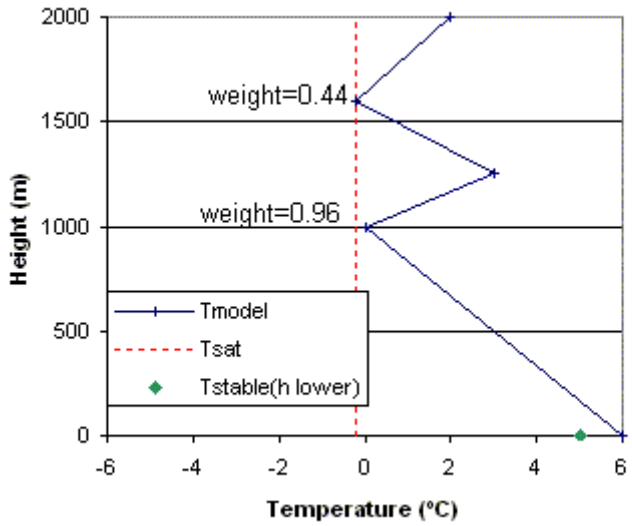


Figure 2: Showing two examples where two stable layers are present. Upper: The stable layer with a base at 1000m is weak and does not match T_{sat}. The higher stable layer with a base at 1600m matches the T_{sat} value and the layer between the two stable layer bases is less stable than the stable lapse rate (T_{stable}). Lower: Both stable layers closely match T_{sat}, but the layer between the two stable layers is more stable than the stable lapse rate by 2.8K, so the higher stable layer is penalised by a factor of 0.44 even though it is a closer match to T_{sat}.

Stable Layer Algorithm (preferred)



Since clouds are normally topped by a stable layer (which prevents the cloud air-parcels from rising further) (Figure 1), this algorithm seeks to place every analysed cloud top at the base of a model layer where the model temperature profile is stable. For every cloudy pixel (determined by the cloud mask input generated in a separate program) the algorithm looks at each layer in the model 3D temperature field (working up from the lowest layer) and considers each layer which has a lapse rate more stable than -5K/km. The layer with the best acceptable fit to the measured Meteosat IR satellite temperature, determined using a form of cost function, is used as the result of the CTH scheme.

At each stable layer, the observed IR satellite temperature (T_{sat}) is compared to that expected from the cloud top temperature at that layer after taking into account the cooling

effect of the atmosphere (from the RTTOV program T_{RTTOV}). Where this falls in the limits $T_{RTTOV} - 5K < T_{sat} < T_{RTTOV} + 3K$, a likelihood is determined for comparison with other possible layers. A maximum weight is given when $T_{sat} = T_{RTTOV}(h)$, where h represents the height of the current level. This weight then decreases linearly as ΔT ($\Delta T = T_{RTTOV} - T_{sat}$) increases, until a weight of zero is given at the limits described above.

As it is expected that the CTHs will be at a level where T_{model} is warmer than T_{sat} would suggest (the mesoscale model does not have the vertical

resolution to resolve the base of an inversion well, the resultant smoothing gives a warmed stable layer base), a larger range is allowed for that.

Because several cases have been found where ΔT > 5K when very shallow cloud or fog exists below a near-surface inversion, an additional 'fudge' has been included. When the algorithm considers a model level below 1km above sea level, an additional brightness correction of 3K km^{-1}×(1,000m-h) is applied to increase the allowed range of ΔT by up to 3K. This allows the algorithm to consider these extremely low cloud cases.

There is one final adjustment to the weighting function. This is done to deal with cases where more than one stable layer could reasonably be fitted to the satellite temperature using the above limits. This tries to ensure that the cloud top is placed at the base of the most stable layer or the lowest layer. The method is illustrated in Figure 2. The temperature at the base of each stable layer is extrapolated to the surface, assuming a lapse rate of 5K/km. The resultant surface temperature is defined as $T_{stable}(h)$, for a stable layer base at height h. Then, working from the surface upwards, if $\Delta T_{stable} = T_{stable}(h_{upper}) - T_{stable}(h_{lower})$, then the additional weight factor, to be combined with the weight factor from the ΔT calculations, will decrease linearly from 1. to 0. as ΔT_{stable} increases from 0K to 5K (outside these limits, the weight will remain constant at either 1. or 0. as appropriate).

For the lowest stable layer, $T_{stable}(h_{lower})$ is taken as the lowest model level temperature. Note that only the RTTOV corrected model temperature at the base of the stable layer is used in matching the satellite temperature.

Figure 2 illustrates how the algorithm works and a detailed flow chart is given in the appendix. In the upper figure, ΔT_{stable} is negative for both stable regions, so the weighting from the additional 'test' is 1 in both cases. However, as the upper T_{RTTOV}=T_{sat}, so this is selected with an overall weight of 1. In the lower figure, ΔT_{stable} is again negative for the lower stable layer. However, for the upper stable layer, ΔT_{stable} is 2.8K so it is penalised by a factor of 0.44. Thus, even though the upper T_{RTTOV} is closer to T_{sat}, the overall weight is lower and the cloud top is placed at the base of the lower stable layer. In physical terms, the algorithm is implying that in the lower case, cloud is unlikely to penetrate the lower stable layer.

Model Temperature Profile-matching Algorithm

When the Stable Layer Algorithm is unable to produce an acceptable result (where the model temperature profile does not have a stable layer that can be used: This frequently occurs, especially in dynamic cloud areas), the Model Temperature Profile-matching Algorithm seeks to place the CTH at the height where $T_{RTTOV} = T_{sat}$. A linear interpolation of T_{RTTOV} is carried out between the two model levels which contain the value of T_{sat} to find a CTH value.

These algorithms are described in a logic flow diagram in the Appendix: Logic Flow Chart.

Changes to Output

Nearly every cloudy pixel is diagnosed with a different CTH in the new scheme compared to the current operational scheme. In the majority of cases, where the model temperature profile-matching algorithm is used, the CTHs have moved towards the surface by only a few metres, with this change increasing as the CTH tends to the lower atmosphere, this is due to atmospheric cooling of emission temperatures now being accounted for.

In the cases where there is low level stratus or stratocumulus or even fog (where it is detected in the cloud mask), the Stable Layer Algorithm is very successful at placing the CTH below the top of the stable layer, usually at the base of the stable layer (the true CTH will usually be a little higher than this). This can result in a change in CTH by up to 3km in extreme cases. The Stable Layer Algorithm matches all the cases determined by the previous Low level Inversion Algorithm as well as many more cases.

All cases where the Stable Layer Algorithm is implemented will result in the CTH being placed at one of the local model levels.

Very deep cloud with a CTH at the tropopause can produce T_{sat} values below the model tropopause value. Previously this would produce a CTH about 5km above the tropopause where the model profile temperature matches T_{sat} (or the highest model level). The new scheme catches most of these cases (placing the CTH close to, or slightly above the tropopause), but some are still missed where T_{sat} is more than 5K below $T_{RTTOV}(tropopause)$ where the model temperature profile is incorrect.

Due to the low vertical resolution of the Mesoscale Model, inversions are often poorly defined in the temperature profile. The smoothing effect imposed on the profile can increase the minimum temperature related to the inversion by several Kelvin and the height associated with the inversion will be moved to one of the model levels. This can result in T_{inv} and $T_{RTTOV}(inv)$ being more than 5K warmer than the satellite observed T_{sat}. In these cases, the CTH is still placed above the stable layer, and may still cause unrealistic results from later programs.

When the cloud in a pixel is broken, the satellite measures the mean radiance which is converted to a T_{sat} value between the true cloud top temperature and the surface temperature. As no information on the continuity of the cloud is available, the cloud is assumed to be continuous. This results in T_{sat} being matched to the RTTOV temperature profile, with a resulting CTH closer to the surface than the true CTH. This is not thought to cause any problems in other programs.

A thin layer of Cirrus with a low emissivity can cause a similar problem to broken cloud, but in the opposite direction. The Cirrus can reduce the IR emission temperature detected by the satellite by more than 5K. When this occurs over low cloud which is beneath an stable layer, T_{sat} can be shifted out of the acceptable range for the appropriate stable layer. In this case, the scheme reverts to interpolating the RTTOV temperature profile and can

place the CTH in a dry layer in the middle of the troposphere. These cases are not common, but their effects are unknown.

The CTH logic will misdiagnose clouds above a warm front where the advancing warm front cloud is thin or broken giving a T_{sat} value contaminated with surface IR emissions. In this case, T_{sat} can be less than 5K cooler than the temperature at the base of the warm front inversion. The logic will then place the CTH incorrectly at the base of the inversion.

Case Studies

The Changes to Output discussed above are shown with ground truths in this section.

Successful Application of Stable Layer Algorithm

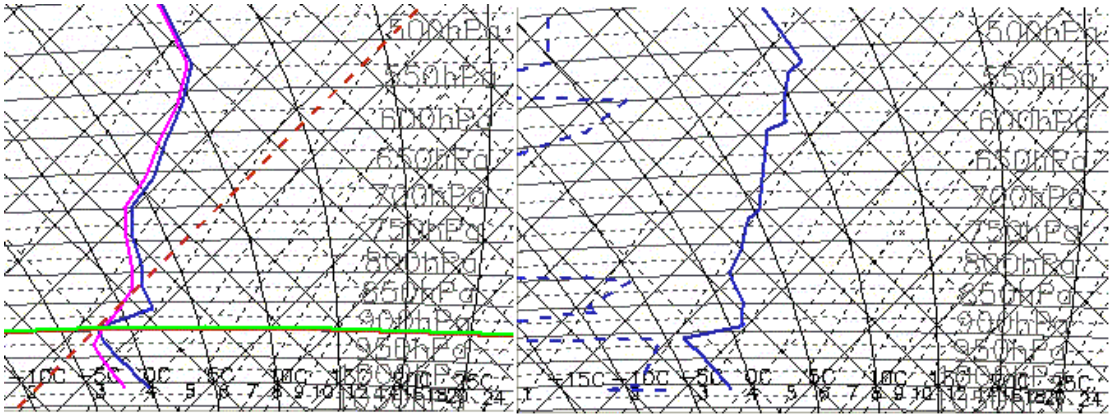


Figure 3: Model, Satellite and Radiosonde data at Ekofisk (WMO 01400) on 31/12/02 at 12Z. Left: Model temperature profile (blue) and RTTOV temperature profile (pink), satellite IR temperature (dashed red) and calculated CTH (green). Right: Dry bulb (solid) and Dew point (dashed) temperature profiles from radiosonde assent.

Ekofisk is a Norwegian Oil Rig in the middle of the North Sea (Lat. 56.53N Lon. 3.21E – Nimrod Grid point 224E 160S).

Figure 3 shows a case where the Model profile closely matched the actual profile where an inversion was present at 900hPa with a base temperature (T_{inv}) of –8.5ºC. The observed satellite temperature (T_{sat}) was –8.5ºC and the RTTOV profile shows that a CTH at 900hPa would have an emission temperature of –8ºC. Since these numbers are all well within the ΔT limit of 5K, the CTH has been correctly diagnosed at the base of the inversion. Using the simple profile matching algorithm, the CTH would have been placed at approximately 840hPa, inside the dry layer above the inversion.

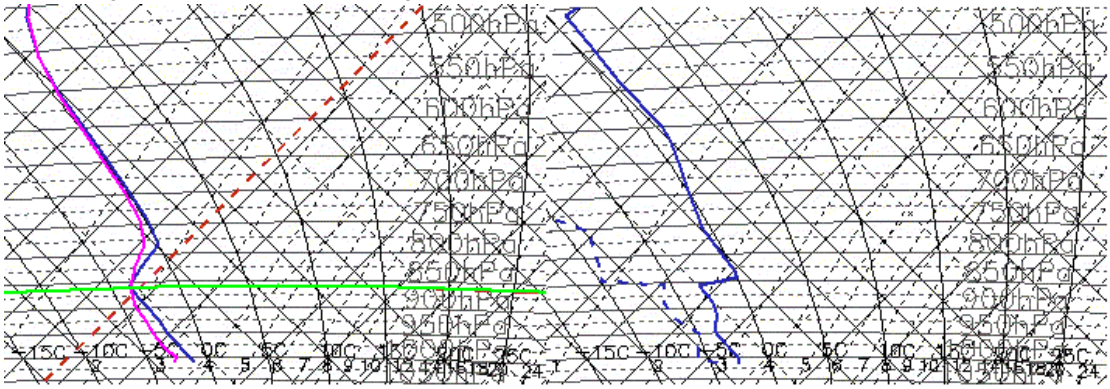


Figure 4: Model, Satellite and Radiosonde data at Emden (WMO 10200) on 6/1/03 at 12Z. Left: Model temperature profile (blue) and RTTOV temperature profile (pink), satellite IR temperature (dashed red) and calculated CTH (green). Right: Dry bulb (solid) and Dew point (dashed) temperature profiles from radiosonde assent.

Figure 4 shows data from Emden in North Germany of another case similar to that shown in Figure 3. Here the inversion is represented in the model by a stable layer with the base height and temperature very similar. T_{sat} is slightly warmer than the base of the stable layer in this case. The CTH diagnosed is plausible and also fairly accurate.

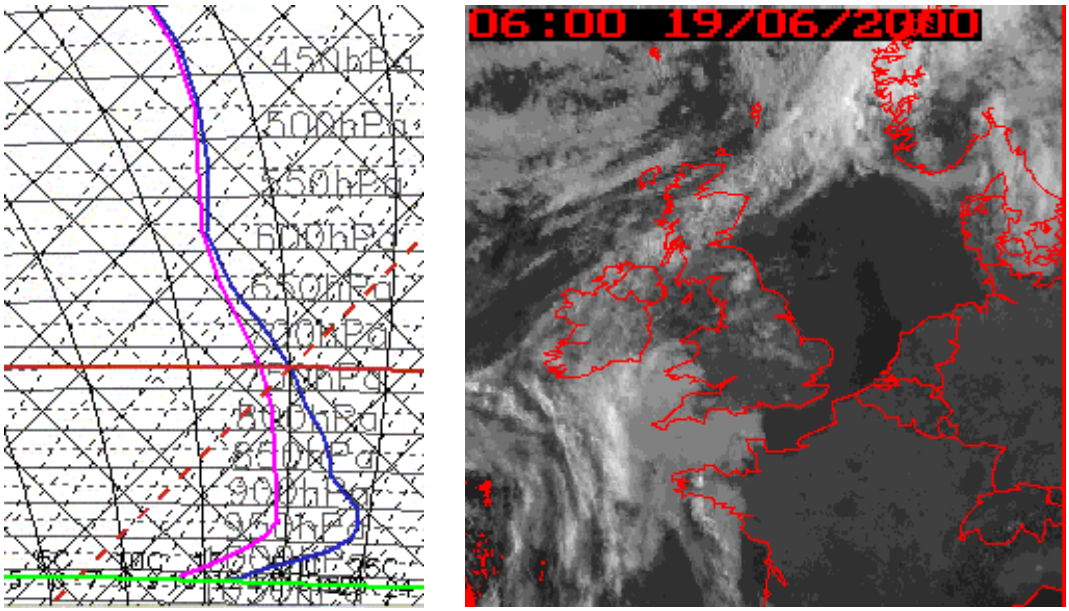


Figure 5: Model and Satellite data from grid point 135,333 (SW English Channel) at 06Z on 19/6/00. Left: Model temperature profile (blue) and RTTOV temperature profile (pink), satellite IR temperature of 7.5°C (dashed red), CTH from stable layer algorithm (green) and CTH from model temperature profile method (red). Right: Corrected Meteosat Visible image showing a large shallow bank of cloud in the western English Channel.

Figure 5 shows a case which NMC reported as causing spurious convection in the mesoscale model. Without the RTTOV profile, the CTH is placed at 725hPa (~2.5km), well into the conditionally unstable layer. The RTTOV profile allows the Stable Layer Algorithm to correctly diagnose the existence of surface fog at this point so long as the additional 3K 'fudge' is allowed for near surface layers.

Successful Application of the Profile-matching Algorithm

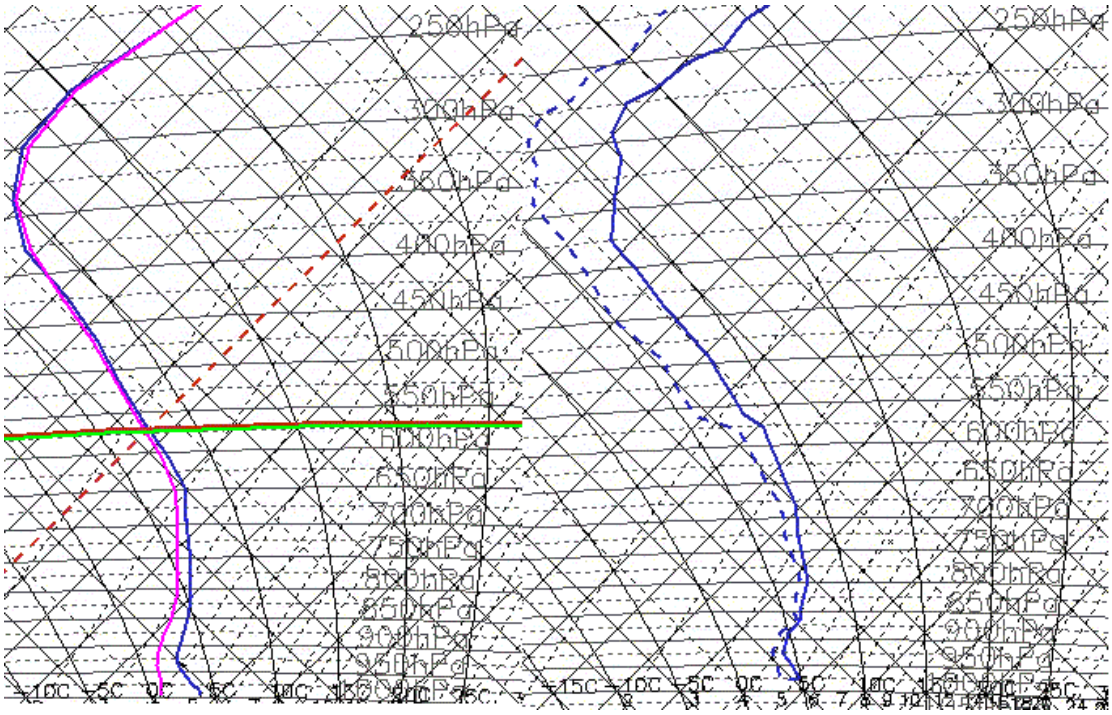


Figure 6: Model, Satellite and Radiosonde data at Nottingham (WMO 03354) on 3/1/03 at 00Z. Left: Model temperature profile (blue) and RTTOV temperature profile (pink), satellite IR temperature (dashed red), calculated CTH from RTTOV profile (green) and CTH calculated from Model temperature profile (red). Right: Dry bulb (solid) and Dew point (dashed) temperature profiles from radiosonde assent.

Figure 6 shows an example where the cloud layer is not topped by a stable layer. The Stable layer Algorithm has failed to find a stable layer within 5K of the T_{sat} value of –22°C. There is a slight separation between the Model temperature profile and the RTTOV temperature profile. This has caused the calculated CTH to be a few metres closer to the surface than was the case when the uncorrected model profile was used.

Errors caused by Poorly Defined Model Inversions

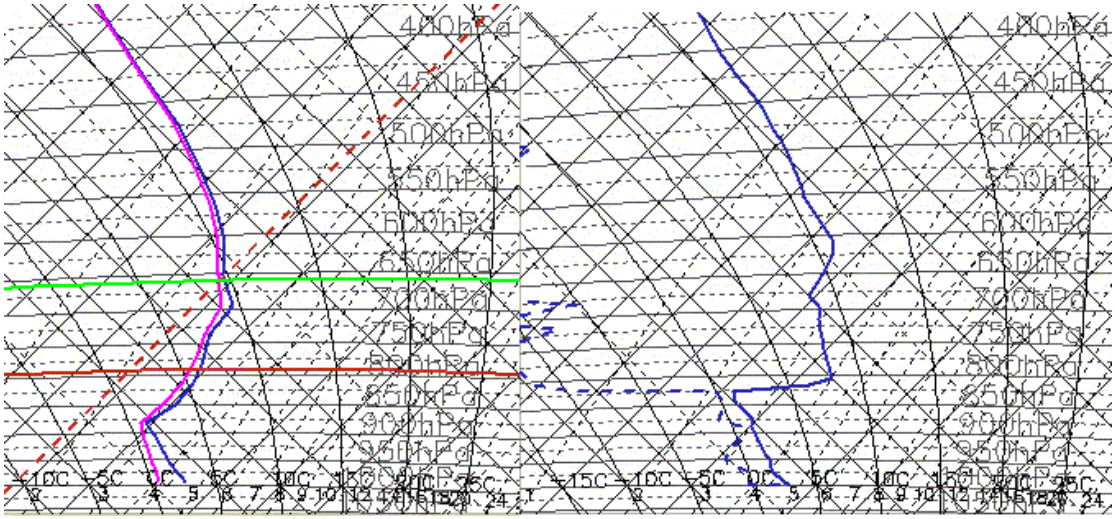


Figure 7: Model, Satellite and Radiosonde data at Nottingham (WMO 03354) on 31/12/02 at 12Z. Left: Model temperature profile (blue) and RTTOV temperature profile (pink), satellite IR temperature (dashed red), calculated CTH from RTTOV profile (green) and CTH calculated using Normand's Point Algorithm (red). Right: Dry bulb (solid) and Dew point (dashed) temperature profiles from radiosonde assent.

Figure 7 shows a situation where the Mesoscale Model had poorly represented a cloud-top inversion. The adiabatic layers of the atmosphere are well represented, but the inversion between the two layers is represented as a much deeper stable region. The lowest temperature in this stable region is –5.5°C while the true temperature at the base of the inversion is –9°C which the satellite sees as a cloud top temperature of –11°C. The Stable Layer Algorithm sees a temperature difference of 5.5K at the base of the stable region which is outside of the acceptable range. Further up in the stable region, where the temperature difference is less, the layers are penalised by the 'more stable' layer at the base of the stable region making them unacceptable as well. The CTH is diagnosed to be above the stable region at 660hPa by the RTTOV profile matching algorithm. This could potentially cause instability in the next model run.

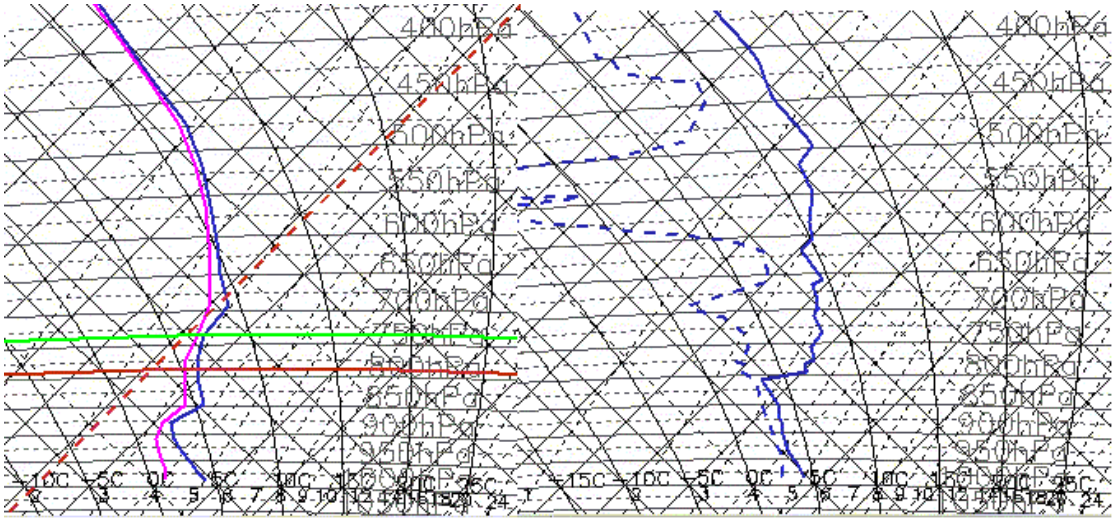


Figure 8: Model, Satellite and Radiosonde data at Albermarle (WMO 03238) on 30/12/02 at 12Z. Left: Model temperature profile (blue) and RTTOV temperature profile (pink), satellite IR temperature (dashed red), calculated CTH from stable layer algorithm (green) and CTH calculated using Normand's Point algorithm (red). Right: Dry bulb (solid) and Dew point (dashed) temperature profiles from radiosonde assent.

Figure 8 shows a case from Albermarle (Northumberland) where the main stable layer in the model profile (the inversion at 875hPa) is at the wrong level. The radiosonde ascent shows the inversion is very definitely at 800hPa where T_{inv}=-7.5°C. The CTH is placed close to the top of the stable layer where T_{RTTOV} is only 1K larger than T_{sat}, close enough that the 'more stable layer' penalty doesn't cause that layer to be discarded too. Although the CTH is incorrectly placed, it is not expected that any problems would result from the placement as it is still inside the model stable layer.

Problems caused by Broken Cloud layers

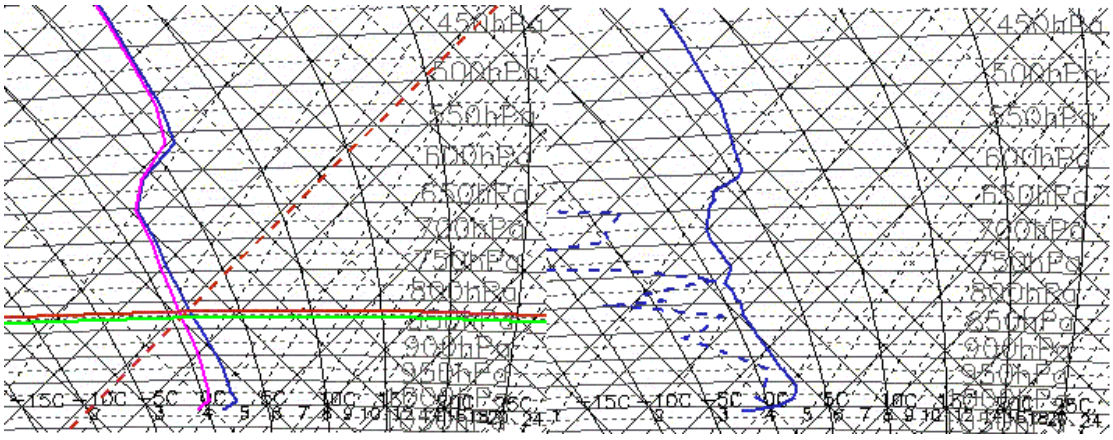


Figure 9: Model, Satellite and Radiosonde data at De Bilt (WMO 06260) on 6/1/03 at 00Z. Left: Model temperature profile (blue) and RTTOV temperature profile (pink), satellite IR temperature (dashed red), calculated CTH RTTOV profile match (green) and CTH calculated using model profile match (red). Right: Dry bulb (solid) and Dew point (dashed) temperature profiles from radiosonde assent.

Figure 9 shows data from De Bilt in the Netherlands. The SYNOP report for the same place and time shows only 1 okta of cloud (base at 7,000' ~2km). This is an automatic station, and the synoptic situation at the time showed

that the station under the leading edge of a cloud bank. It is reasonable to assume that the Laser Cloud Base recorder at the sight had only just started registering the cloud at the time of the observation, hence 4 oktas is more likely. However, in the grid square, we have an unknown covering of cloud, so the satellite will be receiving radiation from the partial cloud cover relating to $T_{cloud\text{-}top}$ and also from the surface in the clear regions relating to $T_{surface}$. Since $T_{surface}$ will be warmer than $T_{cloud\text{-}top}$, we would expect T_{sat} to be too warm. Figure 9 shows this to be the case as the radiosonde shows $T_{cloudtop}$ to be –14°C but T_{sat} is actually –9.5°C.

The result of this is the CTH being placed below the true level, which is unlikely to cause any problems. However the same reasoning is required to explain a bigger problem:

Problems caused by Thin Cirrus clouds

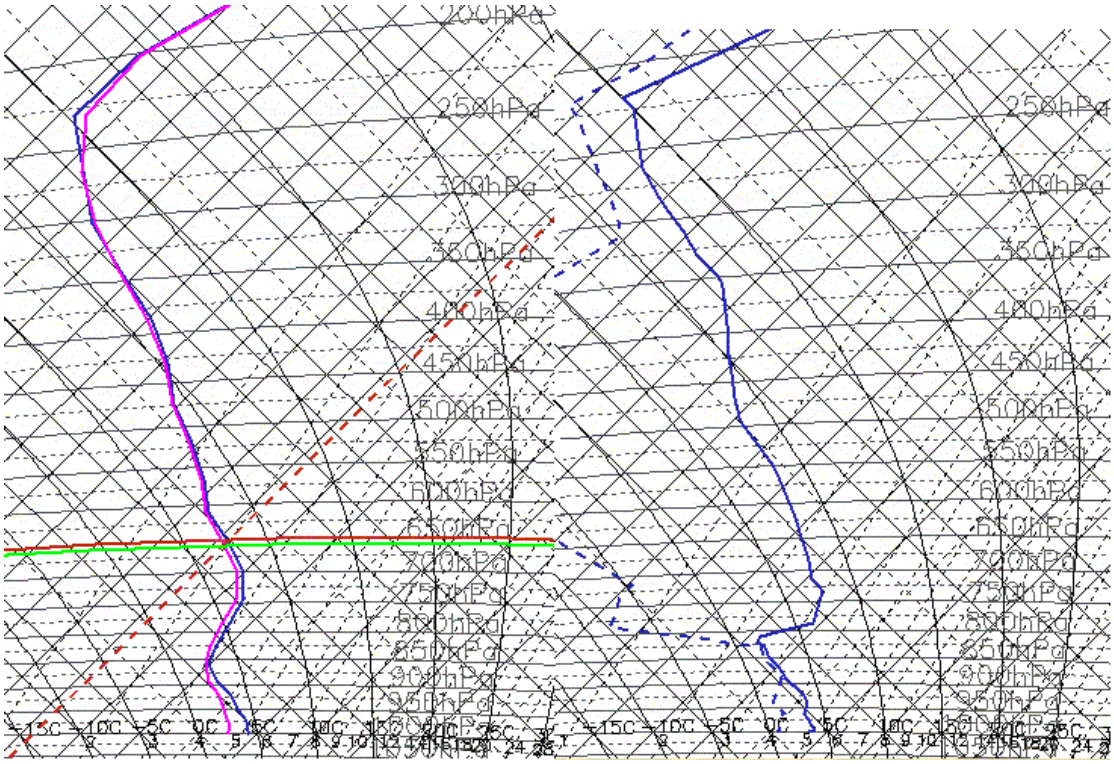


Figure 10: Model, Satellite and Radiosonde data at Camborne (WMO 03808) on 6/1/03 at 00Z. Left: Model temperature profile (blue) and RTTOV temperature profile (pink), satellite IR temperature (dashed red), calculated CTH RTTOV profile match (green) and CTH calculated using model profile match (red). Right: Dry bulb (solid) and Dew point (dashed) temperature profiles from radiosonde assent.

The radiosonde ascent shown in Figure 10 describes a situation where semi-transparent Cirrus is present above boundary layer cloud. The presence of this Cirrus cloud significantly decreases the IR radiation emitted by the boundary layer cloud to the point that the Stable Layer Algorithm cannot fit it to any stable layer, and the RTTOV profile matching Algorithm matches the apparent cloud top temperature seen by the satellite with a position in a dry conditionally unstable region.

A Cirrus cloud with an emissivity of 1/6 and an emission temperature 35K lower than the boundary layer cloud will be sufficient to decrease T_{sat} by the 5K required to become unacceptable to the stable layer algorithm.

A possible solution to this problem would be to include the model 3D relative humidity field in the program, as it has been noted that this field can represent the presence of Cirrus cloud in these situations, along with a check for the possible presence of Cirrus cloud. This approach has not been considered fully as the initial model RH field is determined by the height of cloud determined in this program.

Conclusion

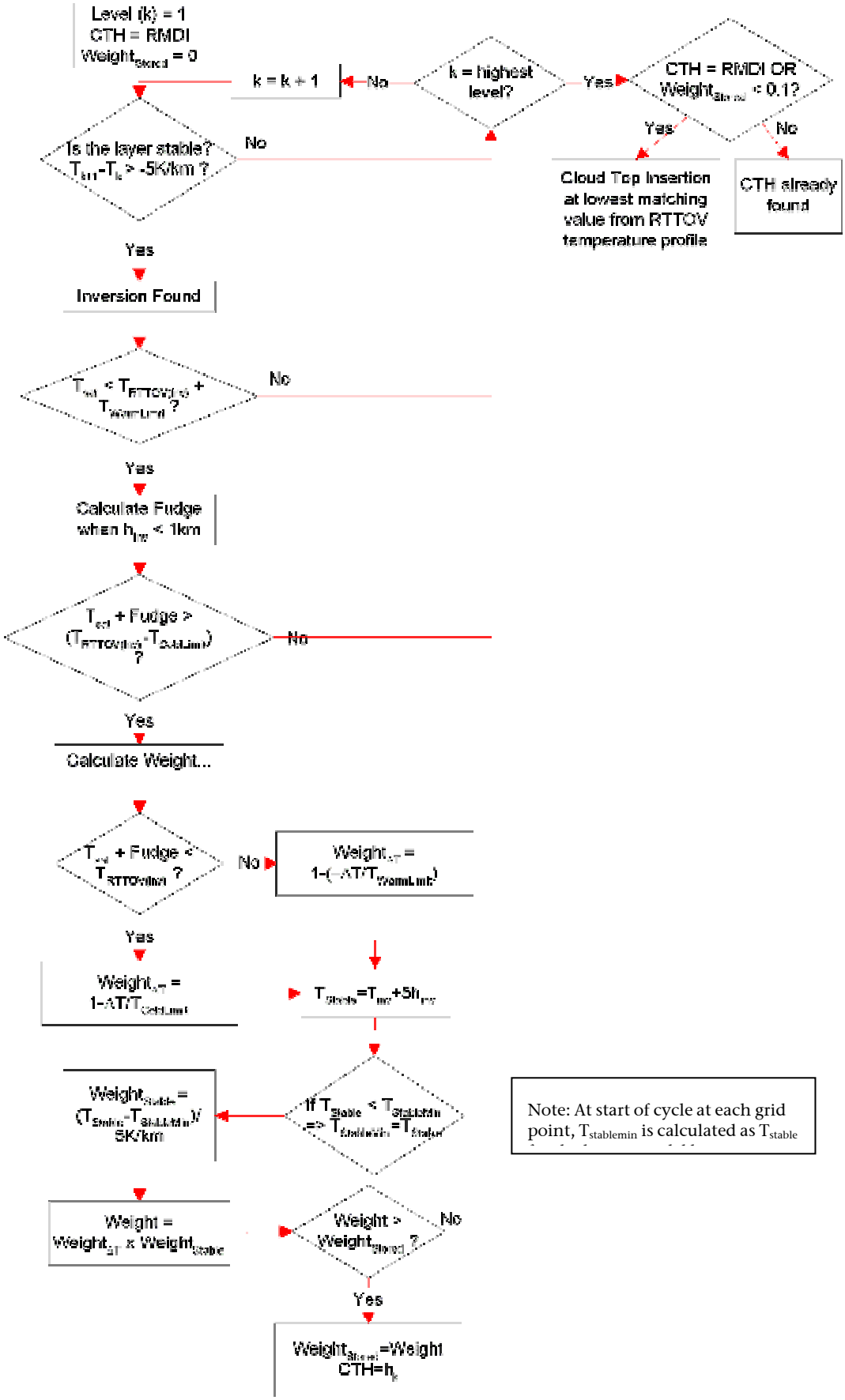
In the majority of cases where cloud exists below a stable layer which is correctly represented by the model temperature profile and no cirrus cloud is present, the Stable Layer Algorithm correctly diagnoses the CTH.

Where cloud exists in the absence of a stable layer, the Model Temperature Profile-matching Algorithm produces a CTH consistent with the RTTOV temperature profile.

The majority of cases which have been studied show that the CTH output will not cause problems in user programs.

There are still some cases where CTH is wrongly diagnosed, and some of these could still cause problems in user programs. The existence of Cirrus above low level cloud is the most likely case to cause problems, as this can still cause the CTH to be placed in a dry region of conditional instability, potentially causing spurious convection in the Mesoscale Model.

Appendix: Logic Flow Chart



Formulaic Logic for Stable Layer Algorithm

At each grid point, first the variables are initialised:

$$w_{stored} = 0.$$

$$k = 1$$

$$T_{\min} = T(k) - h(k)\Gamma_{thresh}$$

Where w_{stored} is the weight given to the level which best fits the satellite temperature T_{sat}, k is the model level number currently being processed (1 is the lowest model grid level, at the time of writing, the highest level was 35, but the highest value of k is $N_{model\ levels} - 1 = 34$), T_{min} represents the most stable level found so far (hence initialised at lowest level), T is the model temperature at level k, h is the model height at level k and Γ_{thresh} is the threshold temperature gradient used to define a stable layer (-5K km^{-1}).
The following sequence of calculations and tests are checked by the program, in order. If any of the tests are false, then k is incremented by 1 and the sequence is restarted:
Layer lapse rate $\Gamma(k)$ is defined as

$$\Gamma(k) = \frac{T(k+1) - T(k)}{h(k+1) - h(k)}$$

$$\Gamma(k) > \Gamma_{thresh}$$

$$T_{stable}(k) = T(k) - h(k)\Gamma_{thresh}$$

where $T_{stable}(k)$ is the level temperature adjusted for height

$$T_{\min} = \min(T_{\min}, T_{stable}(k))$$

$$T_{stable}(k) - T_{\min} < \Delta T_{\min thresh}$$

where $\Delta T_{minthresh}$ is the maximum permitted difference between T_{stable} and T_{min} (5K)

$$\Delta T(k) = T_{sat} - T_{RTTOV}(k)$$

$$\Delta T(k) < \Delta T_{warmthresh}$$

where $T_{RTTOV}(k)$ is the predicted satellite IR temperatuer for a cloud at height k and $\Delta T_{warmthresh}$ is the limiting difference between T_{sat} and $T_{RTTOV}(k)$ when T_{sat} is warmer than $T_{RTTOV}(k)$ (3K).

$$T_{Badjust}(k) = \Gamma_{Badjust}\left[h_{Badjust\max} - \min(h(k), h_{Badjust\max})\right]$$

where $T_{Badjust}$ is the additional brightness correction used to adjust T_{sat} at levels below $h_{Badjustmax}$ (1000m) and $\Gamma_{Badjust}$ is the lapse rate used to determine T_B (3K km^{-1}).

$$\Delta T(k) > \Delta T_{coldthresh} - T_{Badjust}(k)$$

where $T_{coldthresh}$ is the limiting difference between T_{sat} and $T_{RTTOV}(k)$ when T_{sat} is colder than $T_{RTTOV}(k)$ (-5K).
Once all these tests are found to be true, the weight $w(k)$ is calculated:

$$\text{IF } \Delta T(k) < 0 \text{ THEN } w(k) = \left(1 - \frac{\Delta T(k)}{\Delta T_{coldthresh} - T_{Badjust}(k)}\right) \times \left(1 - \frac{(T_{stable}(k) - T_{\min})}{\Delta T_{\min thresh}}\right)$$

$$\text{IF } \Delta T(k) >= 0 \text{ THEN } w(k) = \left(1 - \frac{\Delta T(k)}{\Delta T_{warmthresh}}\right) \times \left(1 - \frac{(T_{stable}(k) - T_{\min})}{\Delta T_{\min thresh}}\right)$$

$$\text{IF } w(k) > w_{stored} \text{ THEN } \begin{matrix} w_{stored} = w(k) \\ CTH = h(k) \end{matrix}$$

Increment k and run algorithm at next level.
When k reaches the level limit of $N_{model\ levels} - 1$, the cycle stops. If $w_{stored} < 0.1$, then the stable layer algorith fails to produce a valid CTH.